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Research and Development Technical Report

ECOM-75-1305-F

STORAGE CAMERA TUBE WITH NON-DESTRUCTIVE READOUT

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Efforts and accomplishments are reviewed at the conclusion of a storage camera-tube contract. This was a follow-on to the development started on Contract No. DAAB07-73-C-0330, which resulted in a tube capable of dual-mode operation; real-time television or storage with non-destructive readout. Performance of the resulting device approached the goals outlined in Technical Guidelines BD-2, which included mode-switching on command, useful sensitivity at 1.06 μM wave-length, and 6:1 zoom in the stored mode. The follow-effort was aimed primarily

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20. Abstract (con't)

at increasing the quantum efficiency at 1.06 μM and, at the same time, realizing the resolution goal of 900 TV-lines per raster-height. A new tube was designed and fabricated to accommodate a larger diode array target having more resolution elements and a greater thickness for photon absorption. Data from resulting tubes are presented.

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FOREWORD

The work herein reported was conducted under U.S. Army Contract No. DAAB07-75-C-1305. This contract provides for research and development leading to the design, fabrication, and evaluation of a storage camera-tube with non-destructive readout as described in Technical Guidelines BD-2A dated 16 May 1974, U.S. Army Electronics Command; Electronics Technology and Devices Laboratory; Beam, Plasma, and Display Technical Area. This report covers the entire period from 14 February 1975 to 12 April 1976.

The present contract was preceded by Contract No. DAAB07-73-C-0330, which resulted in Hughes Type H1325 Storage ~~Camera~~ Tube. That device approached the goals of the applicable Guidelines (BD-2) with 6 1/2% quantum-efficiency at 1.06 μM wavelength. Work on the new contract was aimed at further increase of quantum-efficiency in combination with the other goals of the revised Guidelines, including resolution of 900 TV-lines per picture-height, 6:1 zoom in the storage mode, 60-second minimum reading time, among other objectives, most of which were achieved or approached on the previous contract.

Key personnel who participated in this program are listed in Appendix A.

1.0 INTRODUCTION

The following report reviews the efforts and accomplishments of a program directed toward the continued development of a storage camera-tube. Performance goals are outlined in the Technical Guidelines (See Appendix E). The previous contract resulted in a device identified by Hughes Type No. H1325, which demonstrated the operational characteristics of the desired storage camera-tube and met or approached most of the goals of the Guidelines.

The particular areas where further improvement was sought are those relating to resolution and sensitivity at 1.06 µM wavelength. These two characteristics are related in a trade-off situation involving target-thickness. Increased thickness results in higher sensitivity by virtue of greater absorption of 1.06 µM radiation. However, the greater thickness also allows photon-generated carriers to diffuse greater distances from their points of origin, enlarging the resolution-element.

Of several approaches to higher quantum-efficiency at 1.06 µM discussed in the final report of the previous contract, the one chosen for this continued development was essentially that of increasing target-thickness. In order to preserve or increase the number of resolvable elements in the image, the diameter of the target and dimensions of the image-format were also increased substantially. In addition, the resistivity of the silicon substrate was increased, so that the thickness of the depletion layer, within which lateral diffusion is limited by the field, will also be increased.

The larger target required for this approach entailed a larger overall tube design. This design has been completed and is identified by Hughes Type No. H1349. (See Figure 1-1 and Appendix E).

2.0 ACCOMPLISHMENTS DURING THE REPORT PERIOD

Work was carried on in several areas as outlined below. Efforts during the first period of the contract consisted of planning, design, procurement of materials, tooling, and fabrication of parts and subassemblies. During subsequent periods seven lots of targets were run and demountable tested; a total of twelve H1349 tubes were fabricated and tested. Details follow.

2.1 Large-Diameter Target

The larger two-inch-diameter target is shown front and back in Figure 2-1. The structure is shown in cross-section in Figure 2-2. To put the very large size of this target in perspective, a target from a one-inch silicon vidicon is included in Figure 2-1.

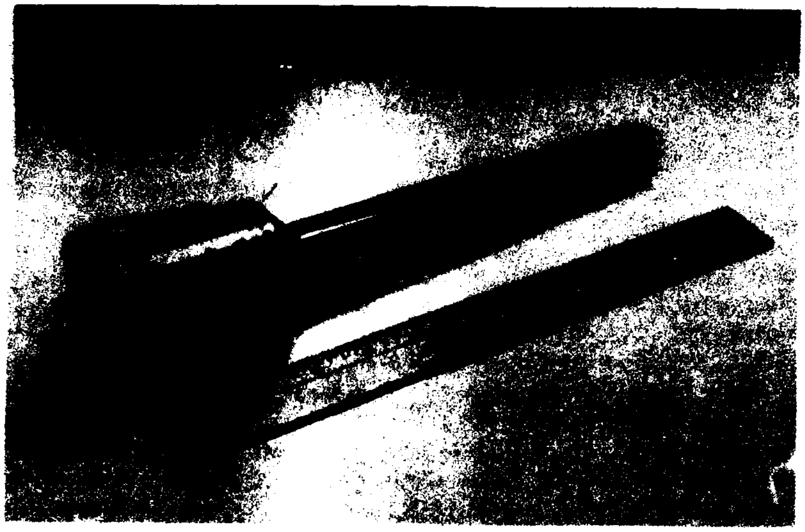


Figure 1-1 H1349 Storage Camera-Tube

Figure 2-1 Two-inch-Diameter Target (Front and Back) Shown with Conventional Target from one-inch Vidicon for Comparison.

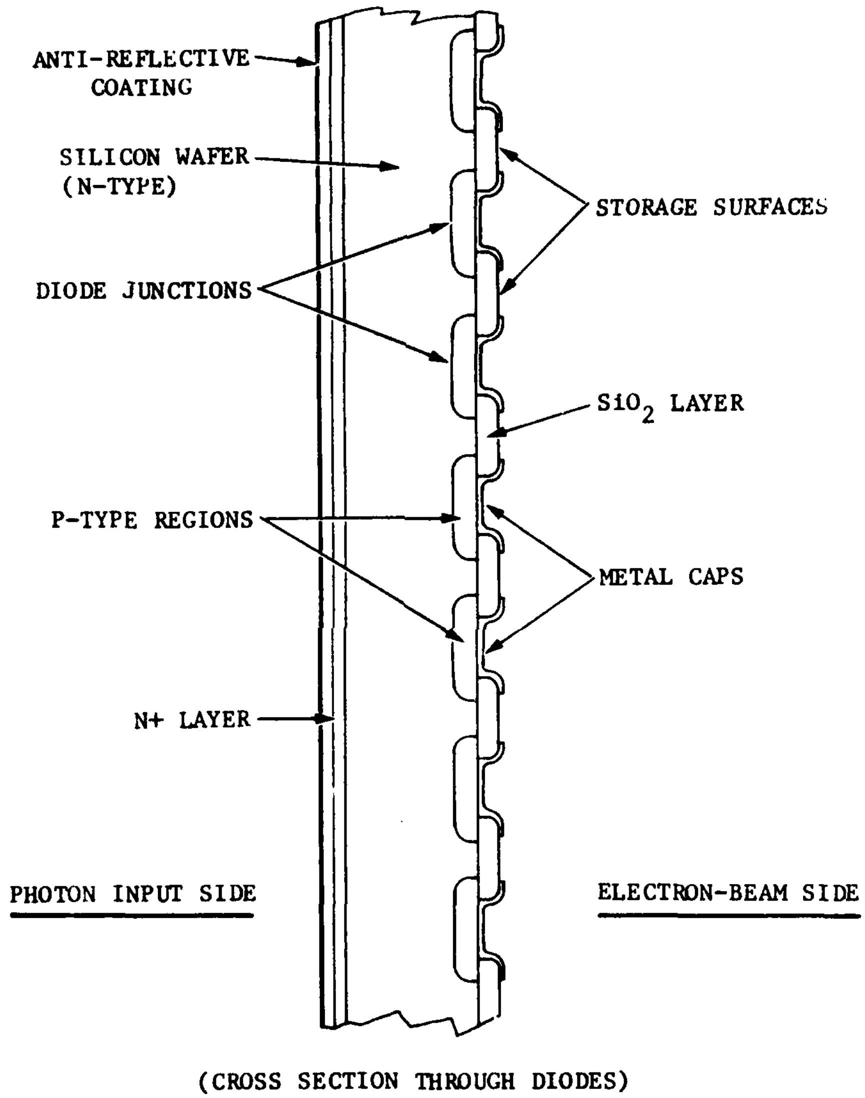


FIGURE 2-2 STORAGE CAMERA-TUBE TARGET STRUCTURE

2.1.1 Material

Two-inch-diameter wafers meeting appropriate specifications were ordered and received. They were cut from Czochralski-grown, n-type material of 50 ohm-cm nominal resistivity and (100) orientation. The vendor was Monsanto. Actual resistivities ranged from 42 ohm-cm to 70 ohm-cm.

2.1.2 Thinning Process Checkout

The larger target-diameter required modification of the thinning equipment. Suitability of the modified equipment was proven initially by practice runs and finally by successful thinning of the first complete lot of targets. Control of final thickness was achieved by sorting unthinned targets so that all targets within a given thinning lot were of very nearly the same thickness (or differing, in some cases, by amounts desired after thinning). A special wafer took the place of one target in each load. This wafer was made thinner at the start by an amount equal to the required final thickness. The process was stopped when that wafer etched through. Final thickness-uniformity generally corresponded to the initial taper of the targets and the tolerance to which targets had been sorted. A variation of less than ± 2.5 µm across the target was typical. A non-contacting capacitance method of thickness measurement was used to determine final thickness of targets used in tubes. Reject targets were sample-checked by micrometer to establish the correlation between the methods.

2.1.3 Reflective Diode-Array Structure

Tests were made of several possible approaches to enhance or maximize the average reflectivity of the back (diode-array) side of the target at 1.06 µM wavelength. These included attempts to electroplate gold over the polysilicon diode caps and to photoetch a deposit of silver over the caps. These metals, which provide the most reflective interface with silicon, cannot survive the temperatures of processes required after target-thinning and therefore must be added to the thinned and fully processed target. The problems associated with photolithography of the thin target were given some consideration and investigated experimentally. Substantial progress was made, but complete success was not achieved within the limitations of available effort.

Recognizing that the polysilicon caps cover only approximately 50% of the surface-area of the diode-array, an upper limit of average reflectivity well below 100% must be expected, even if the reflectivity of the caps is made to approach 100%. An existing computer program at the Hughes Research Labs in Malibu was utilized to calculate average reflectivity for

a variety of conditions. Results indicated that 50% average reflectivity is possible without adding metallic layers, by optimizing the thicknesses of SiO_2 and polycrystalline silicon already present in the structure. This approach was adopted for target lot VID-3 and all succeeding lots.

The optimum layer-thicknesses are very nearly the same as the nominal thicknesses which had been used. However, relatively small deviations from the optimum can result in the minimum average reflectivity of approximately 10%. Therefore, good thickness-control is important. Further details of this study are included in Appendix C.

2.1.4 Anti-Reflection (AR) Coating

Several tests were made, using silicon wafers as received and targets from Lot VID-1, to optimize the choice of material and the thickness of the anti-reflective coating for use on the input surface of the diode-array target. Available materials included two dielectrics and one transparent conductive layer. Thicknesses were determined by process-parameters and ellipsometer measurements of the resulting layers. The ellipsometer also provided a check on the index of refraction of the layer.

Best results were achieved using silicon nitride (Si_3N_4) produced by a chemical-vapor-deposition (CVD) process. The index of refraction was measured to be close to 2.0, which permits virtual elimination of reflection at 1.06 μM wavelength if thickness is near 1325 Å.

The effectiveness of the AR coating was confirmed in several ways. Transmission of 1.06 μM radiation by an AR-coated target was 35% greater than that of the average of three other identical targets without the AR coating. Signal amplitude differences between coated and uncoated areas on the same target were observed both in the demountable and in a sealed-off tube (H1349 No. 2) under uniform 1.06 μM irradiation. The relative signal amplitudes were of the appropriate values to correspond to the virtual elimination of the first-surface reflection. All subsequent targets were coated with this silicon nitride anti-reflective layer.

2.2 Tube-Envelope Modification

Aside from the larger target, the principal change in going from the H1325 to the H1349 involved the tube-envelope. The electron gun remained unchanged. Details of that no-crossover, dual-mode gun design can be found in the Final Report for the prior contract, No. ECOM-73-0330-F.

2.2.1 Initial H1349 Design

The overall tube-design of the H1349 was made such that a substantial portion of the envelope is similar to that of a production tube-type. Modification of the existing envelope design was necessary at the target-

end of the envelope. A new kovar window-flange and a new target-support ring were required. Both of these parts were designed, tooled, and fabricated in sample quantities. The window involved a special faceplate, which was ordered and received. A complete envelope was assembled and sealed under vacuum, then submitted to a pressure-test at 30 psig without any indication of weakness.

2.2.2 Tooling and Envelope Fabrication

New envelope-tooling was required for the window-flange and for the heliarc-seal of the window to the main envelope assembly. These tools were designed, built, and tested by fabrication of parts and assemblies, as already mentioned in Para. 2.2.1.

2.2.3 Design Checkout

The first two H1349 tubes served to confirm the overall design. Both tubes contained targets made using the old mask-set, limiting the diode-array area to 1-inch by 1-inch.

Operation of the first tube was limited by excessive charging of the storage dielectric. The charging prevented good operation in the real-time television mode and precluded mode-switching altogether. These results were not predictable from the demountable test of the target, although they may be consistent with the geometry as recorded on a photomicrograph of the diode array. A better target had not been available when this tube was assembled. The tube proved useful for test-equipment checkout until a better tube became available.

H1349 No. 2 was capable of good operation in both the real-time television mode and storage mode, and it switched modes readily. The resolution goal of 900 TV-lines per raster-height was achieved in both modes, when the pattern size was adjusted to correspond with the larger format of the H1349. The resolution difference between modes which had been encountered on the smaller format of the earlier H1325 was not found on this H1349. Apparently, the diode-array structure is sufficiently fine relative to this larger resolution-element that it can have a negligible effect on stored resolution.

The sensitivity of H1349 No. 2 corresponds to a quantum-efficiency of approximately 5%. This efficiency is less than had been expected, considering that the target thickness was increased to 26 micrometers from 18 micrometers, which had been accompanied by a quantum-efficiency of 6-1/2% in the best H1325. Since the quantum-efficiency depends upon several factors (e.g., carrier-collection efficiency, reflectivities of both target surfaces, absorption coefficient of the silicon) in addition to the thickness, it must be assumed that the improvement expected as a

result of thickness-increase was more than compensated by unfavorable changes in one or more of the other factors. The target incorporated its own test of the anti-reflective coating on the input side, in that a portion of the target was left uncoated. The effectiveness of this coating was evident in the operation of the tube, as it had been in the demountable test. (See Paragraph 2.1.4 and Figure 2-3). Therefore, the explanation for the less-than-expected quantum-efficiency must be sought in the collection efficiency, absorption coefficient, or the reflectivity of the diode-array side. The last factor was discussed in earlier Paragraph (2.1.3), and the absorption coefficient in Appendix D. There is no known reason to suspect a loss of collection efficiency in this target; however, this possibility has not been ruled out.

2.3 Tube Fabrication and Test

During the program a total of seven lots of silicon diode-array targets were run and 12 storage camera-tubes were fabricated. The targets for the 12 tubes were selected from the seven lots on the basis of target behavior in a demountable test equipment. The more significant details of the fabrication and test activities are reviewed in the following paragraphs.

2.3.1 Target-Processing.

Most processes were carried over from the previous contract with minor changes. Target-fabrication utilized conventional techniques, in general, for achieving the structure represented in Figure 2-2. The less conventional processes included use of 1:1 projection mask-alignment, use of chemical-vapor-deposition (CVD) in vacuum for the polycrystalline silicon caps, and use of ion-implantation for the n^+ layer. A test of pre-phosphorus gettering showed no advantage and was not adopted. There was not significant reduction in numbers or sizes of blemishes, or lowering of dark-current. The vacuum polysilicon process, on the other hand, produced a smoother layer than the conventional CVD process, which uses a carrier gas at atmospheric pressure.

2.3.2 Demountable Testing

The demountable test station shown in Figure 2-4 was used to screen targets prior to thinning and again after AR-coating to select targets for use in H1349 tubes. The carousel target-holder accommodates six of the two-inch-diameter targets. The test consisted of visual inspection of the monitored display, with the target in the dark and again with the target flooded with light and erased to a low halftone in the storage mode. Most blemishes are visible under only one or the other of these two conditions. Few are visible under both. Reasons are

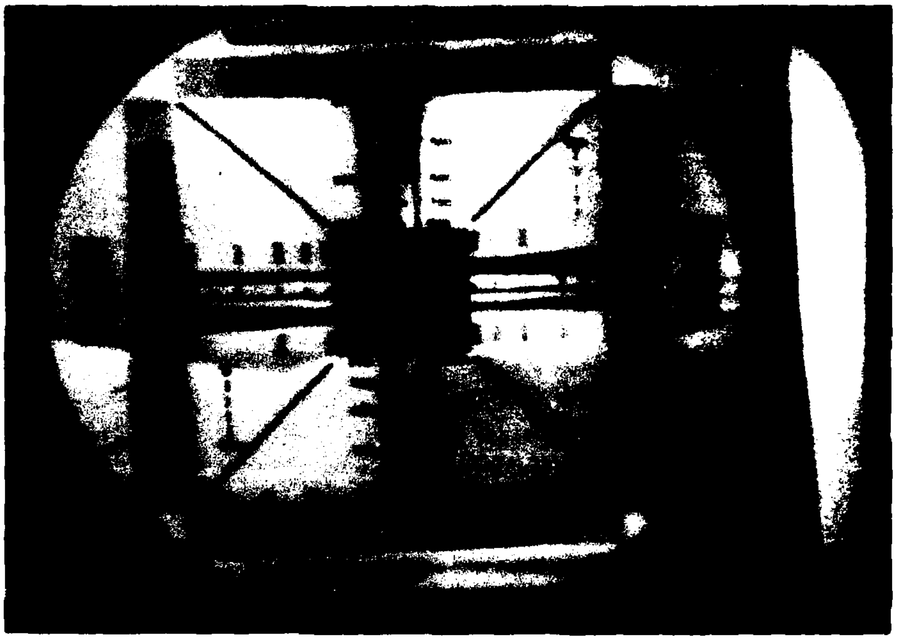


Figure 2-3 Signal from H1349 No. 2.
(AR coating was omitted from upper left portion.)

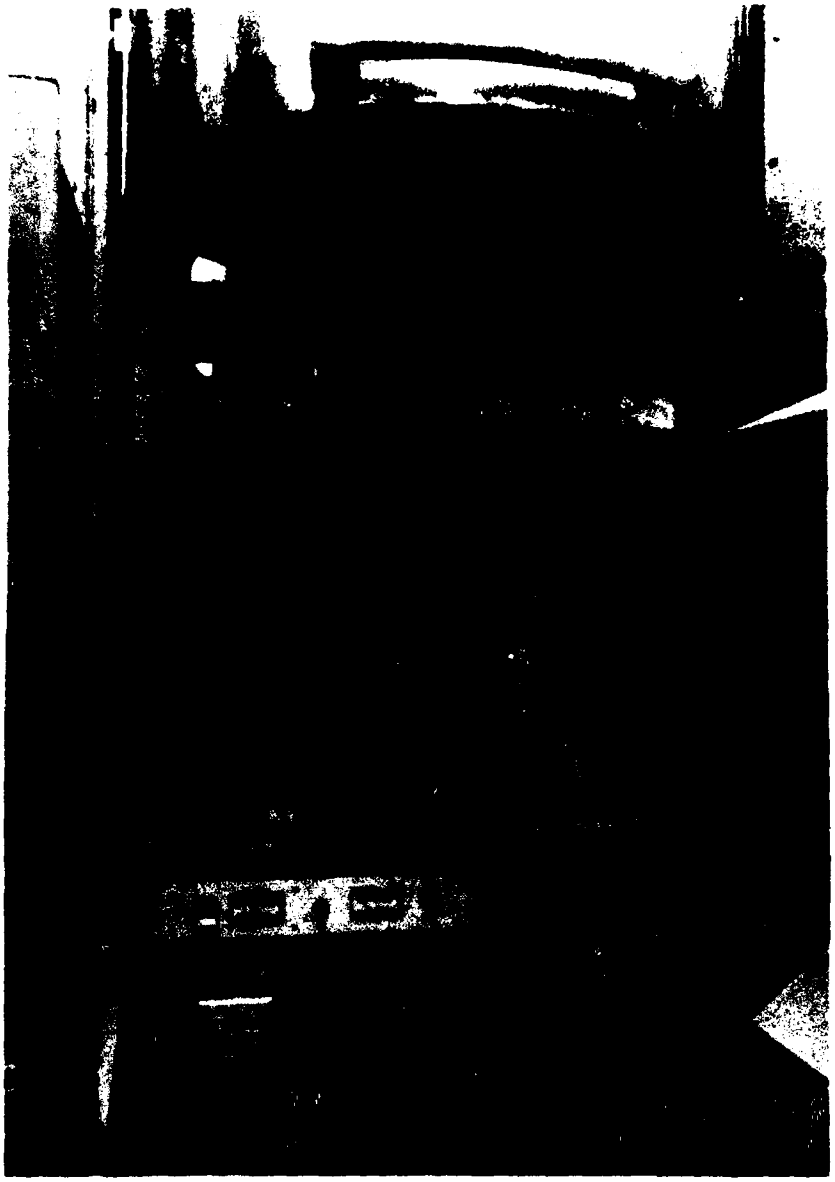


Figure 2-4 Demountable Target-Test Station

that the blemishes in the dark are generally caused by leaky or shorted diodes, whereas those visible in the storage mode represent irregularities in the surface-geometry affecting control of beam-landing on the diodes, which are saturated by light. Photomask quality is a major factor in the quality of the stored image.

Semi-quantitative indications of dark-current and of storage characteristics were obtained in the demountable. Accuracy of these measurements was limited by illumination of the target by the hot cathode and by positive-ion neutralization of charges on the storage-surface. The demountable test combined with microscopic examination and visual inspection provided the basis for selection of targets for use in tubes.

2.3.3 Tube Processing

The assembled tubes were baked on exhaust at 375°C for 3 hours. This process resulted in an excellent vacuum after tip-off and getter-flash, and minimized ion-charging during non-destructive readout.

2.3.4 Tube Testing

The storage camera-tube test-equipment from the previous contract required modification to adapt it to the larger H1349 design and its electron-optics. The similarity in overall design between the H1349 and the H1330 storage-tube made it possible to utilize the Model 639 scan-converter box designed for use of the latter tube for modification of test-equipment for the storage camera-tube. This scan-converter box was incorporated in both the demountable target-test equipment and the final tube test-equipment. Electrode voltages used for test are given in Table 2-1.

This test equipment, shown in Figure 2-5, was well suited for taking many kinds of data with the aid of available light-sources, optical power-meters, and auxiliary instruments for measurement of currents, voltages, and waveforms. The equipment also provided for mode-switching in accordance with the sequence of Figure 3-4. The mode-switching behavior is not entirely predictable on the basis of characteristic curves of target and electron gun. Therefore, such a sequence is necessary to evaluate performance. The nature of the tube and the storage technique are such that successful operation depends to a large degree on the choice of the parameters in the sequence. Although the sequencer in this test-equipment provided considerable adjustment of voltage-levels, time-parameters were fixed at values which were not always optimum for the available conditions, i.e., lens, light-sources, etc. This restriction did not affect test-results as much as it did the ability to demonstrate operation effectively. A tabulation of the more significant test-data is provided in Table 3-1 in the next section.

Table 2-1 Operating Voltages for H1349

Additional information regarding operating voltages and conditions is given in Figure 3-4 and Table 3-2.

Heater	6.3 volts dc
Cathode	0 volt (reference)
Grid No. 1	+10 volts during reading; 0 to -100 volts during mode-switching sequence (adjust for best operation)
Grid No. 2	+20 to +50 volts during reading (adjust for 2 to 7 μA current on Grid No. 4); +300 volts during mode-switching
Grid No. 3	+450 volts
Collimator L1	250 to 500 volts*
Collimator L2	250 to 500 volts*
Collector Electrode	950 volts
Target	+5 to +8 volts in real-time television mode; +3 to +4 volts in stored mode; +50 volts during erase in mode-switching sequence; +5 to +30 volts during remainder of sequence (adjust for best operation)

*Adjust for best collimation.

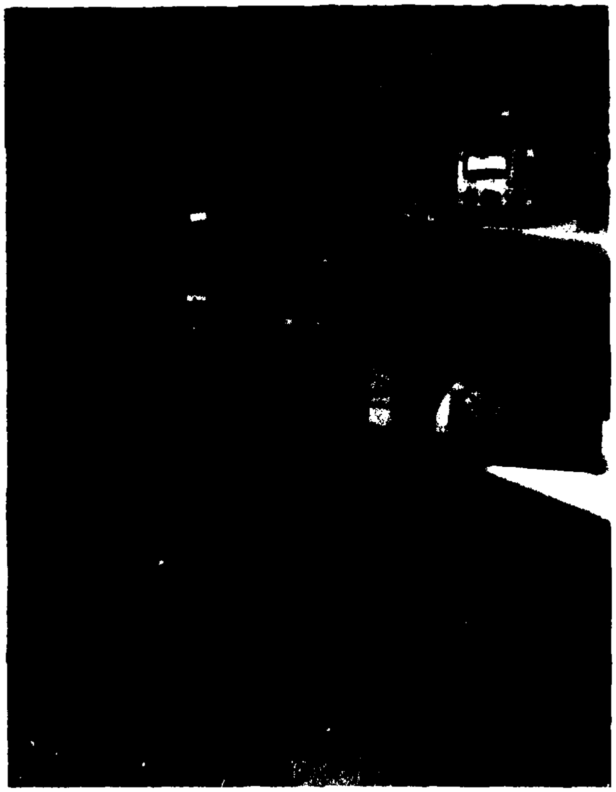


Figure 2-5 H1349 Test Equipment

Tube, with coils and lens, is mounted atop Model 639 Scan Conversion unit near top of rack. Test pattern illuminator is on shelf in background.

3.0 SUMMARY OF TEST RESULTS

Tube testing was concentrated in the areas of performance which were relevant to the particular goals of this follow-on contract, viz., resolution and quantum efficiency at 1.06 μM. On a few tubes plots were made of storage characteristics, spectral characteristics, and dark current characteristics, and best conditions for mode-switching were recorded. These results are presented in the accompanying figures and tables, with the intent that they be generally self-explanatory. Reference will be made to some of these data in later paragraphs. A number of photographs of monitored outputs from tubes are also included. These photographs will be discussed under appropriate topics below.

3.1 Resolution

The values of resolution tabulated in Table 3-1 were measured in the TV-mode on a 40-mm-diagonal pattern-size. Units are TV-lines, limiting, per raster-height. As already mentioned in Paragraph 2.2.3, the stored resolution is not measurably lower than the real-time TV-resolution on this 32 mm X 24 mm format. The 2000 diodes-per-inch array does not appreciably limit resolution. The major factors limiting the resolution are lateral diffusion of carriers in the target and the beam-diameter. Figure 3-1 is a display of stored resolution on H1349 No. 2, reading non-destructively in the zoomed mode. The trade-off of resolution and quantum-efficiency at 1.06 μM as functions of target-thickness can be detected in Table 3-1.

3.2 Quantum Efficiency and Spectral Response

Measurements of quantum-efficiency at 1.06 μM are tabulated in Table 3-1. The measurement was made using a tungsten source and a 50-Å wide interference filter to illuminate a masked area of one square centimeter in front of the target. An optical power-meter (UDT Model 21A) was used to measure the watts per square centimeter at the plane of the mask. The target-current was measured with and without the mask-aperture obstructed. The resulting change in target-current was divided by the power-meter reading (corrected by the appropriate calibration factor) to obtain amperes per watt at 1.06 μM. The overall quantum-efficiency was calculated by dividing this figure by .856 amperes per watt representing 100% at 1.06 μM wavelength.

This overall efficiency, as already noted, is a composite of the effects of reflection, absorption, transmission, and collection of photon generated carriers by the diodes. If the absorption-coefficient is known (See Appendix D), a theoretical limit can be determined for the best case of complete control of reflections and 100% carrier-collection efficiency. For example, using 13 cm^{-1} for the absorption coefficient and a target-thickness of 30 μM,

Table 3-1 Summary of Tube Data

H1349 No.	Serial No.	Target No.	Thickness (μM)	Responsivity at 1.06 μM (A/W)	Overall Quantum Efficiency at 1.06 μM	Limiting Resolution (TV-Lines per Pattern-Height)	Dark Current at 8 Volts (nA/cm^2)	Additional Information
1	7525 176	VID1-4	28	---	---	---	--	1-inch-square array. Excessive negative charging.
2	7535 057	VID2-11	26	.043	5.0%	900	38	1-inch-square array. Good mode-switching and storage.
3	7547 141	VID3-8	40	.058	6.8%	800	22	"Grainy" target-texture. First tube using 1.65-inch-square mask.
4	7548 080	VID3-19	35	.054	6.3%	---	--	"Grainy" target-texture. (Opened to salvage electron-gun.)
5	7613 027	VID4-10	30	.046	5.4%	950	12	Mask-related blemishes. First tube having vacuum CVD polysilicon.
6	7615 120	VID6-3	30	.047	5.5%	975	20	Intense ring pattern in output. (Material-related non-uniformity of dark-current.)
7	7616 089	VID5-2	35	.060	7.0%	---	--	Excessive negative charging. (Opened to rework target.)
8	7616 122	VID5-5	43	.058	6.8%	---	--	Excessive negative charging. (Opened to rework target.)
9	7618 007	VID5-6	56	.075	8.8%	750	18	Thick target; poor carrier-collection from input side (See spectral curve.)
10	7618 008	VID5-7	30	.040	4.7%	950	13	Large blemishes.
11	7619 124	VID5-5	43	(.058)	(6.8%)	750	28	Target from No. 8; large leaky area; still has tendency to charge while reading.
12	7620 144	VID5-2	35	(.060)	(7.0%)	900	32	Target from No. 7; still has tendency to charge while reading.

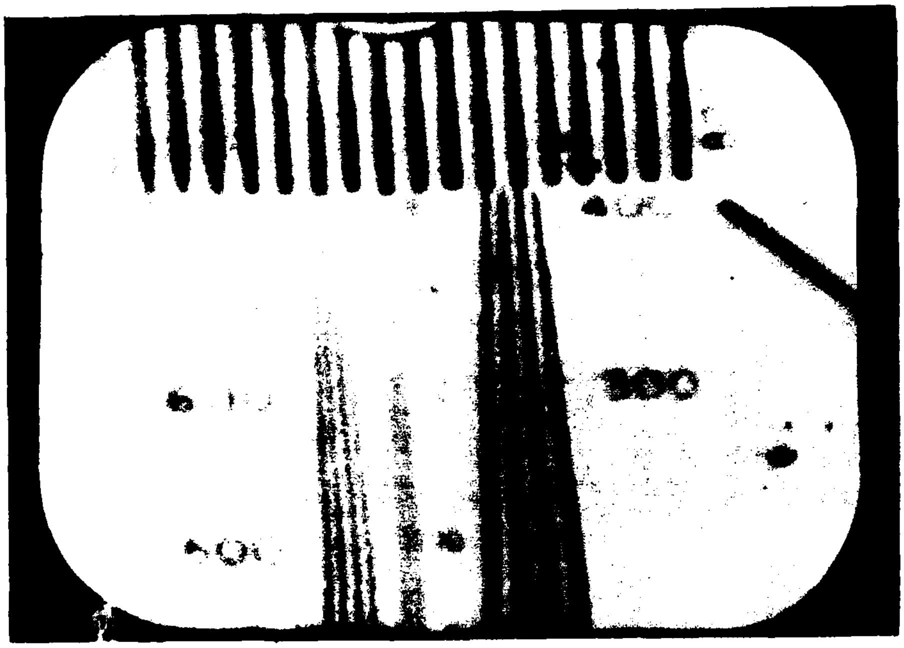


Figure 3-1 Non-Destructive Readout of Stored Pattern in Zoomed Mode.

zero front-surface reflection, total rear-surface reflection, and 100% collection efficiency, the theoretical limit of overall quantum-efficiency would be the percent absorption for 60 μM thickness, or $A = 1-e^{-\alpha t} = 1-\exp(-60 \times 10^{-4}\ \text{cm} \times 13\ \text{cm}^{-1}) = 7.5\%$.

The tabulated measurements appear to be roughly consistent with this theoretical limit, although neither collection-efficiency nor control of reflections can be assumed to be very nearly perfect. In fact, as discussed in Appendix C, rear surface (diode-array side) reflectance of over 50% is improbable with this structure. The spectral response of the thickest target (in H1349 No. 9) suggests poor collection from the front surface, where short-wavelength radiation is absorbed. (See Figure 3-2). However, the other two tubes represented in the figure appear to be better in this respect.

3.3 Dark-Current

One of the problems associated with a large-area diode-array target is the dark-current level. The typical silicon diode-array vidicon has a scanned image size of 1/2 inch by 3/8 inch, which represents an area of 1.2 cm^2. This storage camera-tube has an image-area of 7.7 cm^2, or 6.4 times the usual area (See Figure 2-1). All else being equal, the dark-signal is 6.4 times as great in the larger tube.

All else is not equal, in fact, since some of the material and process parameters for this large target are dictated by considerations peculiar to this tube. For example, the 50 ohm-centimeter silicon-substrate resistivity was chosen to minimize the effect of the thick target on resolution; however, it is unfavorable to low dark-current.

More significant than the absolute level of dark-current are the variations in dark-current from point to point on the array. Non-uniformities which are negligible on a small scanned area may become comparable to the signal in amplitude when the larger area is scanned. The factor of 6.4 applies to both the dark-current level and its variations in the television mode. The situation may be either better or worse in the storage mode, depending upon the time allowed for integration prior to mode-switching and the target-voltage level at which the diodes are charged prior to the integration. It is believed that the solution to much of the dark-current variations must be sought in the silicon substrate material. Curves of dark-current vs. target-voltage for three tubes are shown in Figure 3-3.

3.4 Mode-Switching

The voltage-levels tabulated in Table 3-2 apply to the sequence in Figure 3-4 for the respective tubes. The alternate set of conditions for tube No. 2 represents a significantly different operation from the set above.

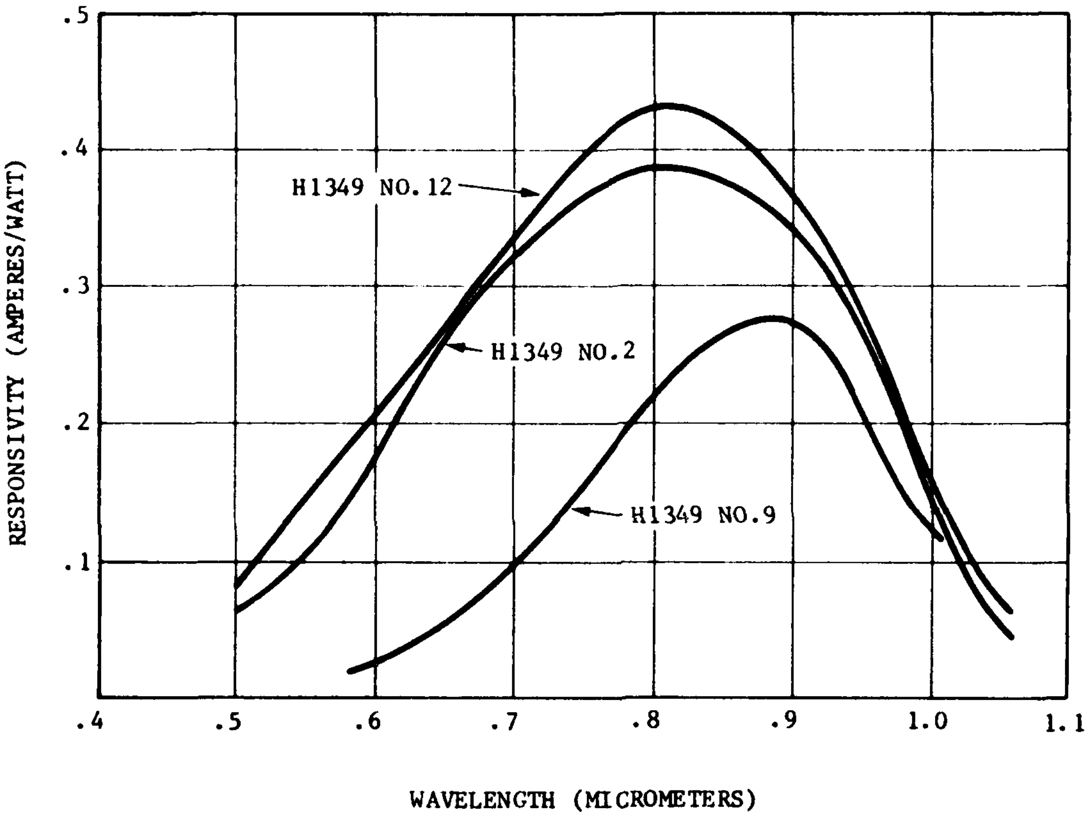


FIGURE 3-2 SPECTRAL CHARACTERISTIC

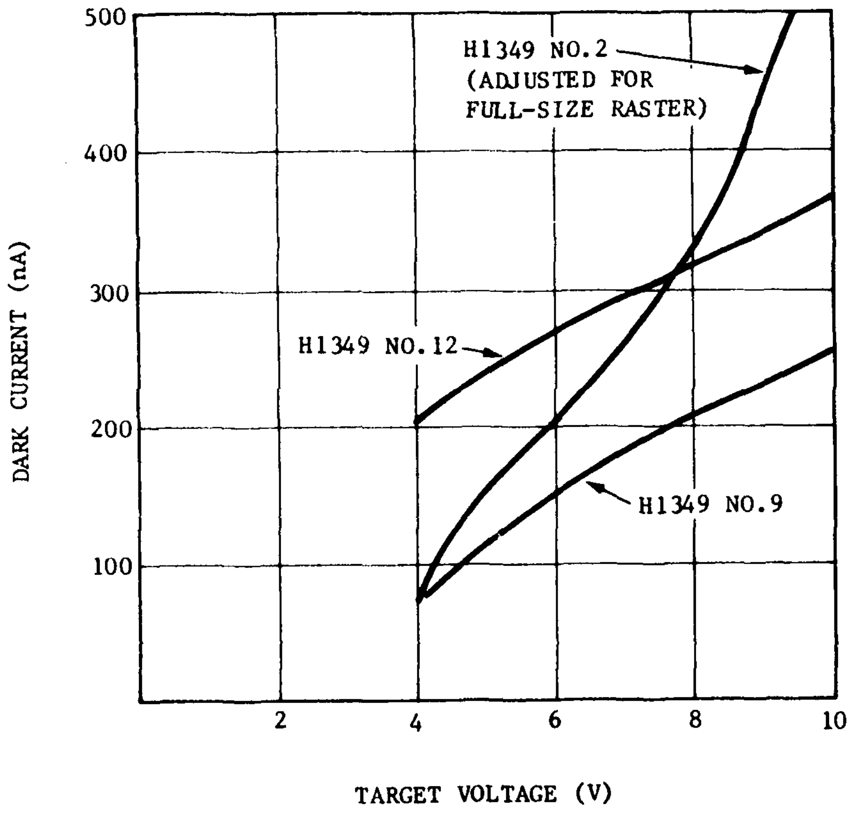


FIGURE 3-3 DARK-CURRENT CHARACTERISTICS

TABLE 3-2 MODE-SWITCHING POTENTIALS

(See Figure 3-4 for Sequence)

TARGET VOLTAGE

Tube No.	Erase	Prime	Store	Non-Destructive Read
2	55	9.5	23.0	3.5
2 (Alternate)	55	10.5	28.5	3.5
3	55	13.5	23.0	3
7	55	11.0	24.0	4.5 (short storage-time)
9	55	18.0	25.0	4.0

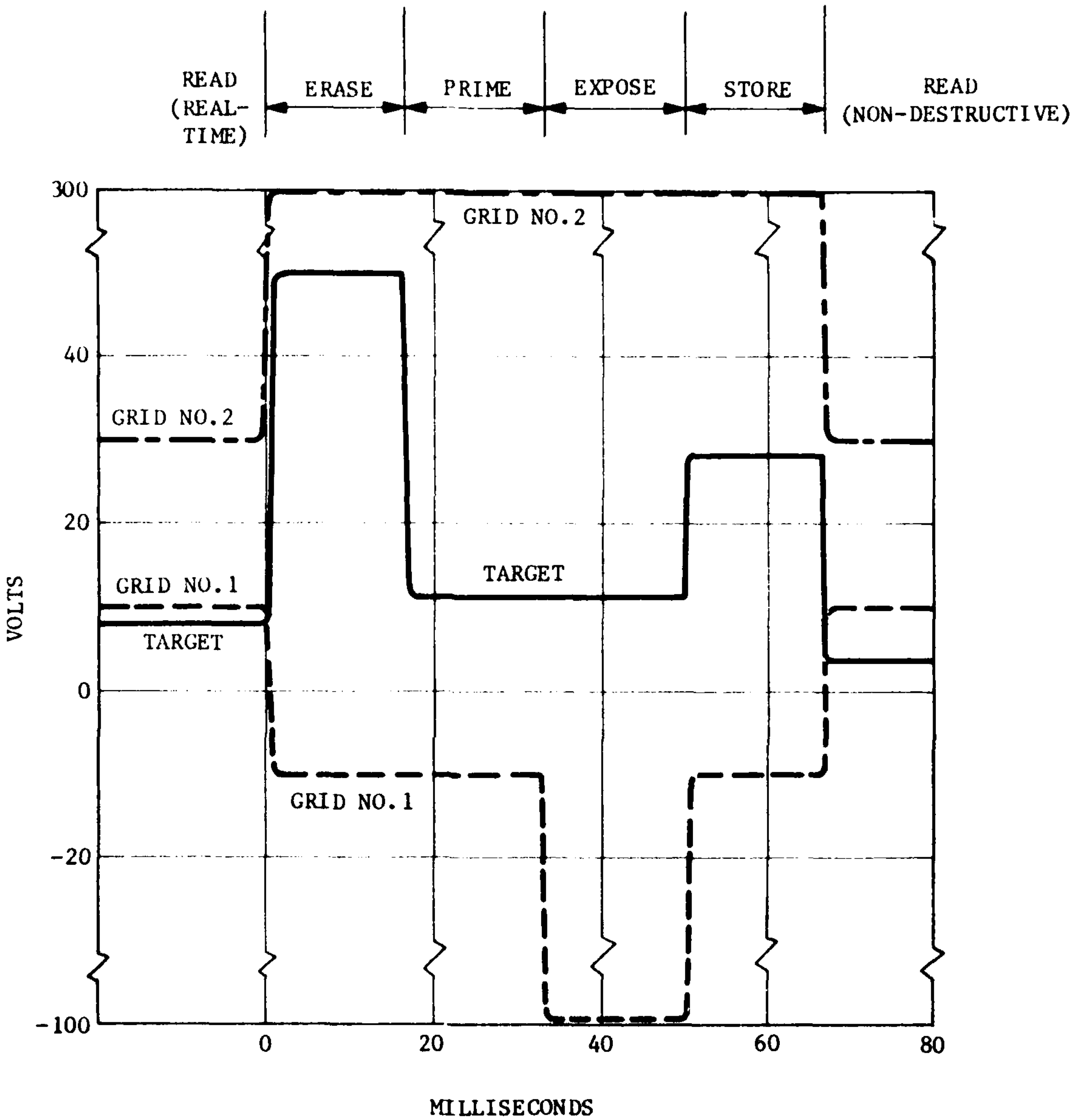


FIGURE 3-4 MODE-SWITCHING SEQUENCE
(TYPICAL POTENTIALS)

In the alternate conditions, the dielectric potential is actually shifted to varying degrees in the positive direction during the store operation, whereas, heretofore, negative charging has been employed. Apparently this target surface has a sufficiently high secondary-electron-emission ratio (or low first crossover) to permit this operation. The resulting image-quality is somewhat better than that using negative charging, which occurs at a lower target-potential. No mode-switching occurs at the intermediate potentials. These alternatives are less distinct on other tubes.

After mode-switching, the output-signal vs. stored potential is determined by the storage-characteristic of the target, as illustrated in Figure 3-5.

3.5 Excessive Charging by Reading Beam

Several of the targets exhibited a problem of excessive negative charging by the reading-beam. The most probable cause of this effect in the past has been the exposure of too much dielectric surface around the diodes. When the geometry is correct, the exposed oxide surface is sufficient to provide control of beam-landing on the polysilicon diode-caps in the storage mode, but not so extensive as to prevent beam-landing on the caps when charged to cathode-potential in the television mode. The optimum geometry had been found on the prior contract to consist of polysilicon caps which were approximately three times the width of the exposed oxide between.

Late in the program excessive charging was encountered on targets of geometry which was well within safe limits for oxide-charging. In some cases charging was found to be attributable to a very thin layer of silicon nitride over the diode-array side, which was deposited inadvertently during the AR coating of the opposite side. This thin layer was readily removed and resulted in much reduced charging. Tubes Nos. 11 and 12 incorporated targets from Nos. 7 and 8 which were reworked to remove possible nitride and any oxidation of the polysilicon caps. A slight tendency toward charging still remains, however, although target-geometry is more favorable than in tube No. 2, which shows no such tendency.

The process-sheets provide no clue to the remaining charging; however, there are several possibilities. Slight oxidation of the polysilicon caps may have occurred during tube-processing, although this seems unlikely. Or a very thin insulating layer may exist between the diode and the polysilicon cap in spite of precautions to avoid it.

3.6 Target-Quality

Besides the blemishes mentioned in Paragraph 2.3.2 and dark-current uniformity discussed in Paragraph 3.3, all tubes display to a greater or lesser degree the step-and-repeat pattern which is inherent in

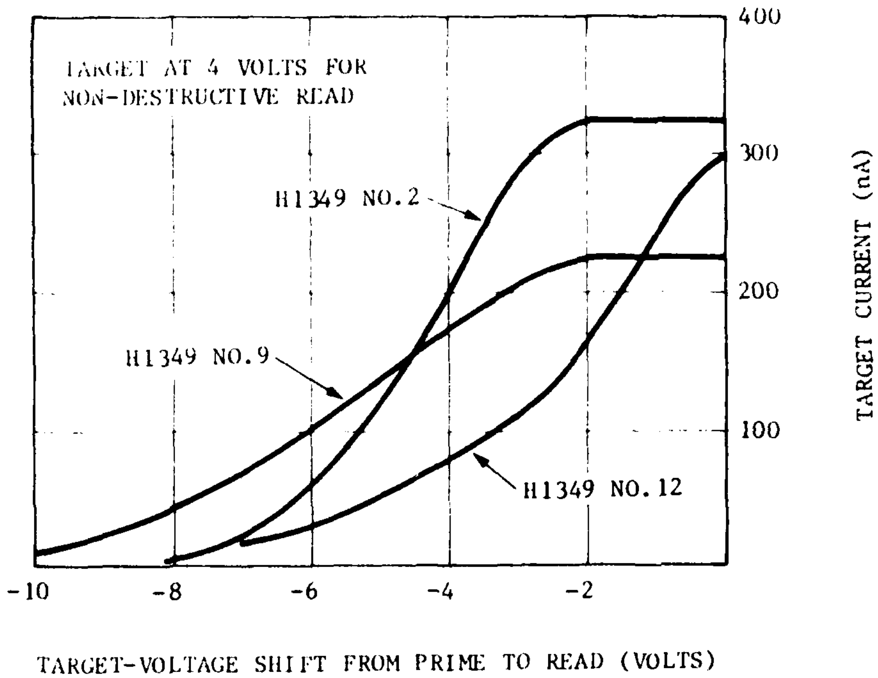


FIGURE 3-5 STORAGE CHARACTERISTICS

the method of photomask-generation. All of these problems are apparent in one or another of Figures 3-6 to 3-12.

4.0 CONCLUSIONS AND RECOMMENDATIONS

A device as defined by the Technical Guidelines BD-2A is feasible, if the phrase "comparable useful sensitivity at 1.060 micrometer" can be satisfied by 6% to 8% quantum efficiency. The H1349 Storage Camera-Tube design is capable of the defined operation. However, several problems remain to be solved before such a tube can be fabricated economically and with acceptable quality. These problems include:

1) generation of large-area photomasks of high quality without step-and-repeat patterns,
2) identification and control of excessive negative-charging mechanism,
3) control of the level and uniformity of dark-current,
4) definition of application parameters so that mode-switching sequence and tube can be optimized for intended use.

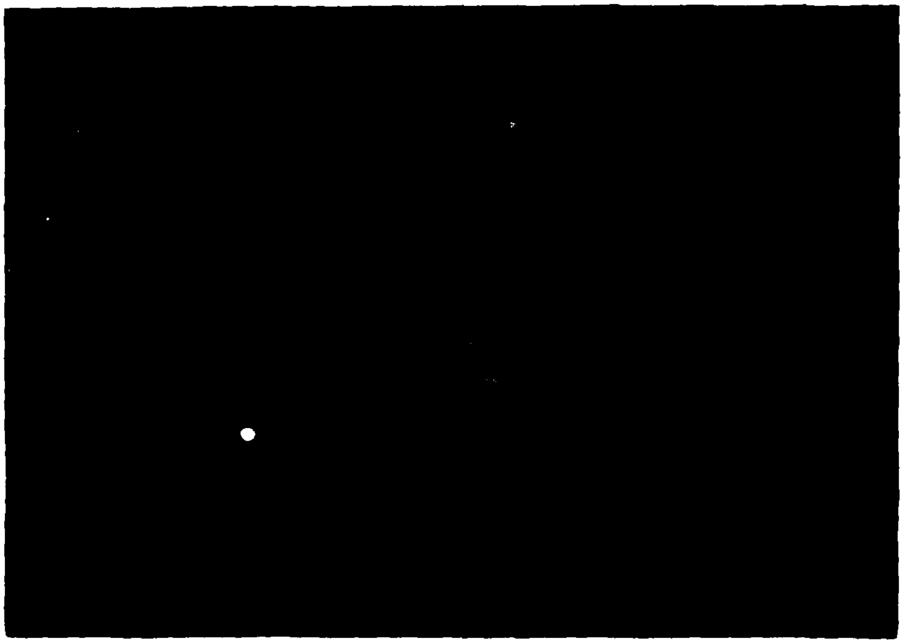
Specific solutions can be proposed for each of the first three problems above. To eliminate the step-and-repeat pattern, a mask-set can be derived from a ruling from a laser-controlled ruling engine. Such rulings are used very successfully in Hughes scan-converter storage-tubes, which function almost exactly like this storage camera-tube when in the non-destructive-read mode. The second-level mask for the diode-caps is most critical. Diode registration within the cap is less critical and, if necessary, might be satisfied with a step-and-repeat-generated mask for the first level. An alternate approach to the step-and-repeat pattern problem is the generation of a hexagonal array of diodes. Although generated by step-and-repeat, the hexagonal array promises to provide a relatively pattern-free output and a geometry favorable to storage operation.

Tests of process variations have been designed to eliminate possible causes of the excessive negative charging. The processes involved are the boron diffusion and tube-exhaust bake. There is a very good possibility of simplifying the target-processing in conjunction with the charging investigation. The reduction in the number of process-steps is generally conducive to better quality and performance.

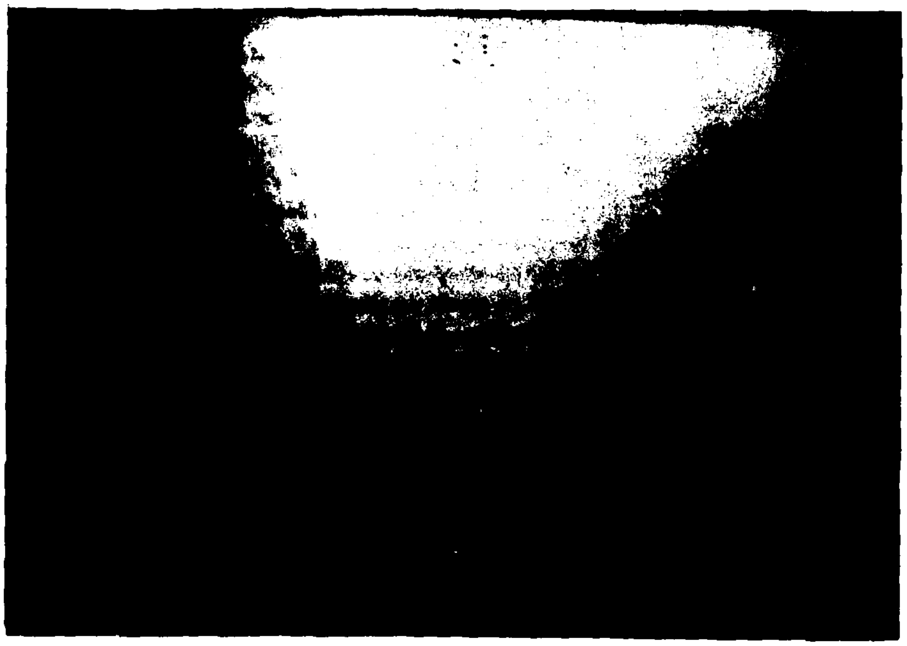
Dark-current level and uniformity are subject to considerable improvement by choice of starting material and process-parameters. Transmutation-doped silicon, by neutron irradiation, can provide greatly reduced radial variations in resistivity. There may be other advantages to the high purity silicon which is used for transmutation-doping. The general freedom from impurities may make the material more stable throughout the process sequence.

Regarding the fourth problem, general-purpose test-equipment with highly flexible circuitry is possible, but the complexity and cost can be reduced if the range of radiation-levels, laser pulse-widths, etc., are defined. As indicated in Paragraph 2.3.4, evaluation of tube-performance requires operation with a mode-switching circuit, at the present state of understanding of the device.

Finally, a modification of the target can be considered for applications of the tube which are particularly critical with respect to 1.06 μM sensitivity and/or gate-width, or rejection of input prior to a given point in time. In the present tube, the open-gate period is bounded on the first side by an erasure operation and on the back side by the storage of the image and illumination of the target for non-destructive reading. The narrowest gate-width is a few milliseconds. A similar target fabricated on a very thick high-resistivity intrinsic silicon substrate would have high quantum-efficiency at 1.06 μM and be capable of gating by application and removal of the field which would deplete the full thickness. Because of the great thickness (.015 to .020 inches), the capacitance would be sufficiently low to be driven with a relatively narrow pulse. The target-structure would be somewhat more complicated than that of the present target shown in Figure 2-2. Mode-switching and image-storage could be provided as in the present device.

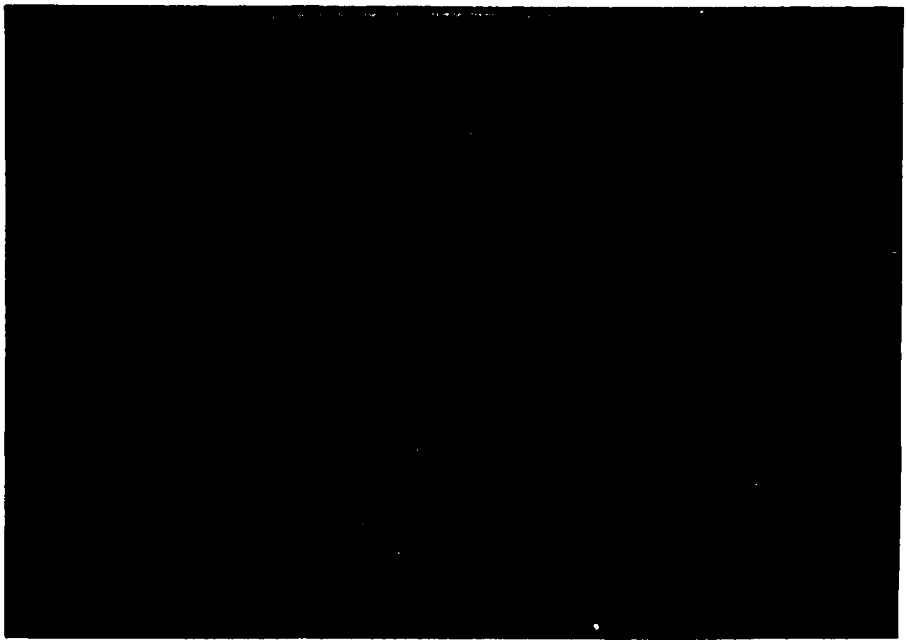


a) Real-time television mode -- in dark.



b) Storage mode -- erased to low half-tone.

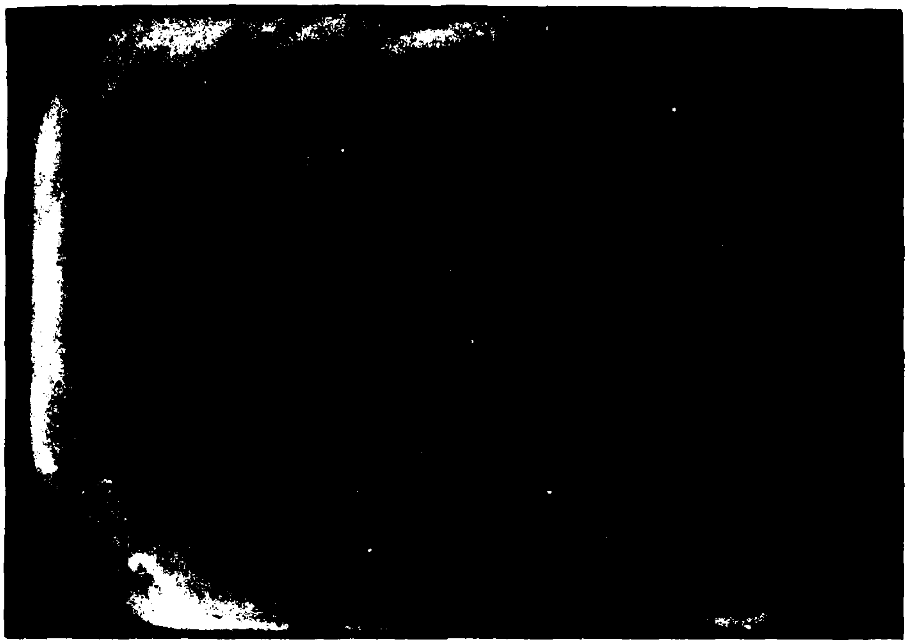
Figure 3-6 Output from H1349 No. 3.



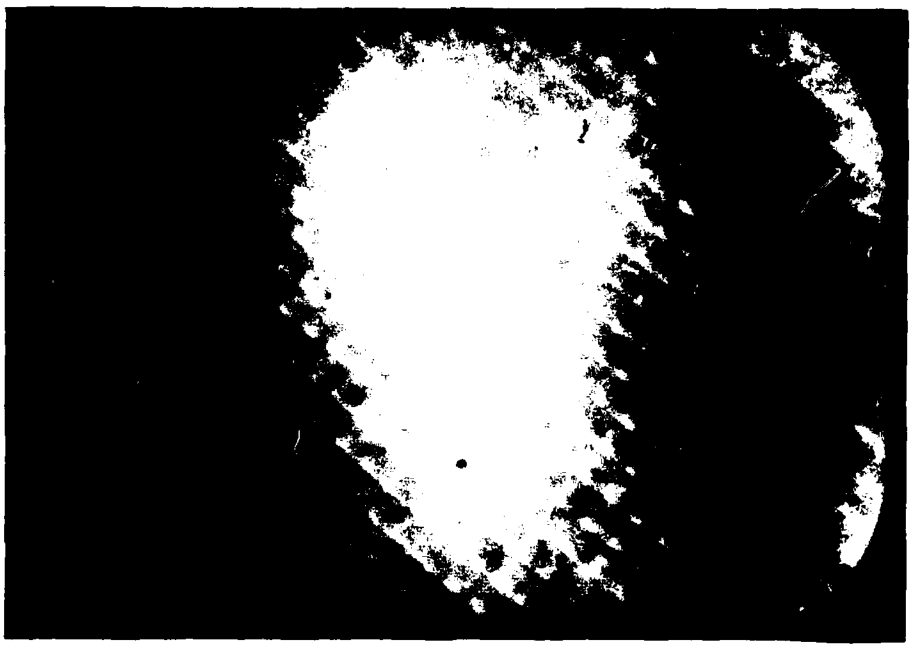
a) Real-time television mode -- in dark

b) Storage mode -- erased to low half-tone.

Figure 3-7 Output from H1349 No. 5.

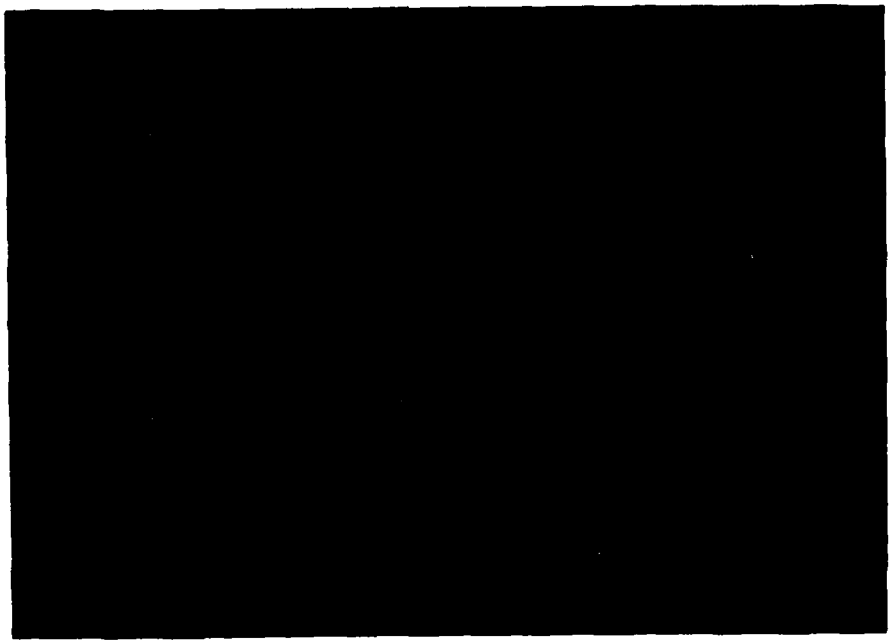


a) Real-time television mode -- in dark.

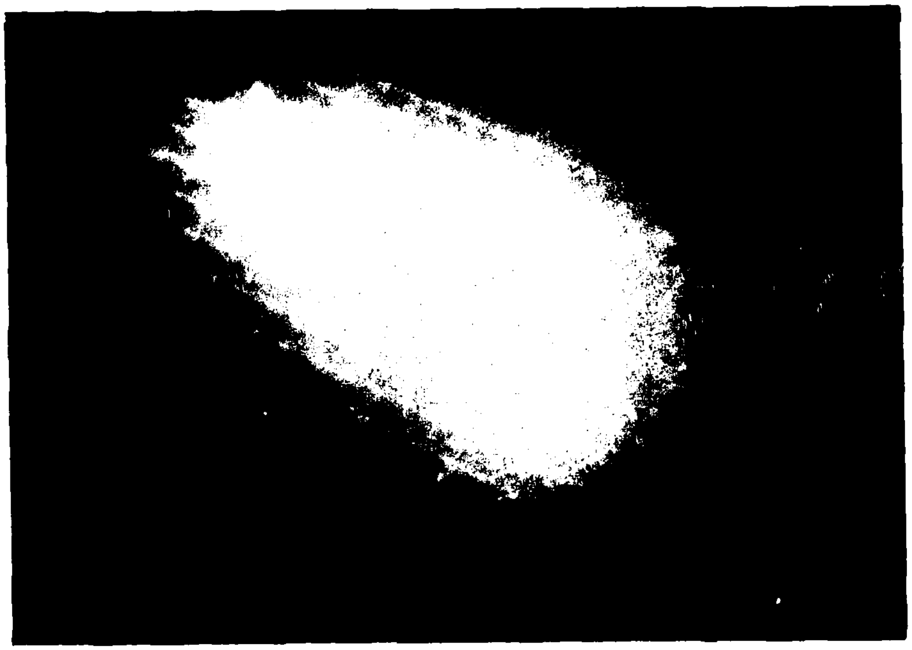


b) Storage mode -- erased to low half-tone.

Figure 3-8 Output from H1349 No. 9.



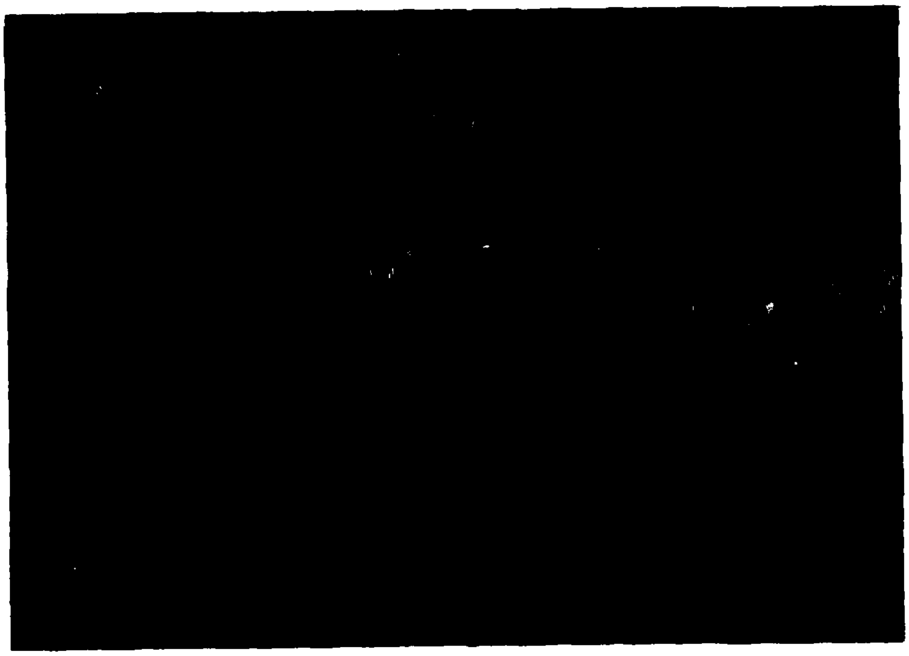
a) Real-time television mode -- in dark.



b) Storage mode -- erased to low half-tone.

Figure 3-9 Output from H1349 No. 9.

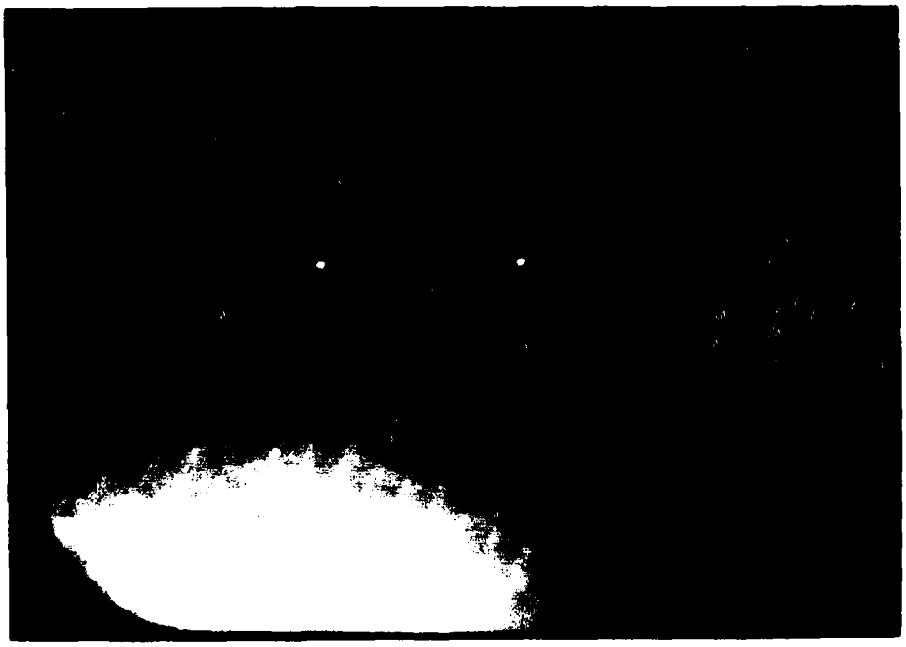
a) Real-time television mode -- in dark.



b) Storage mode -- erased to low half-tone.

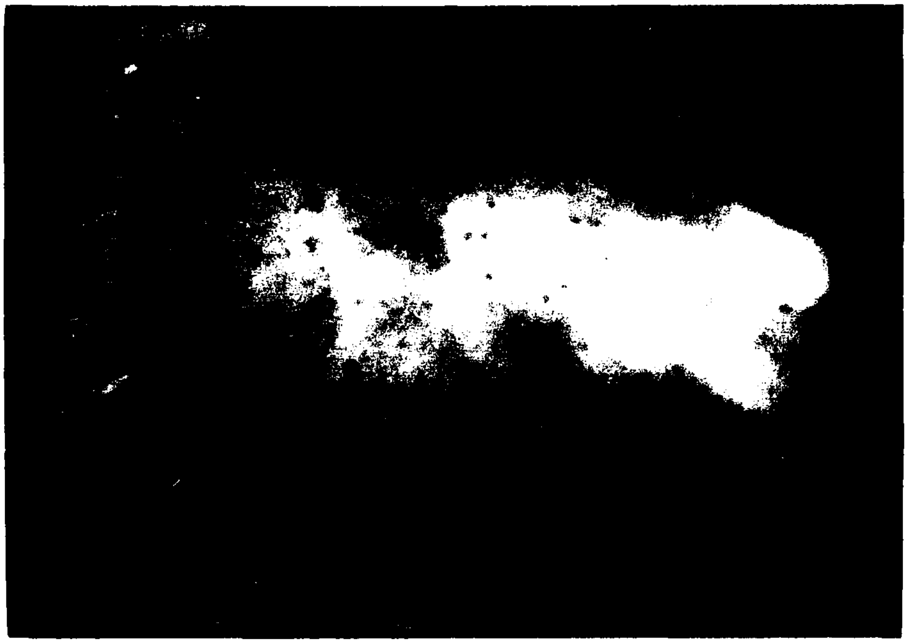
Figure 3-10 Output from H1349 No. 10.

a) Real-time television mode -- in dark.

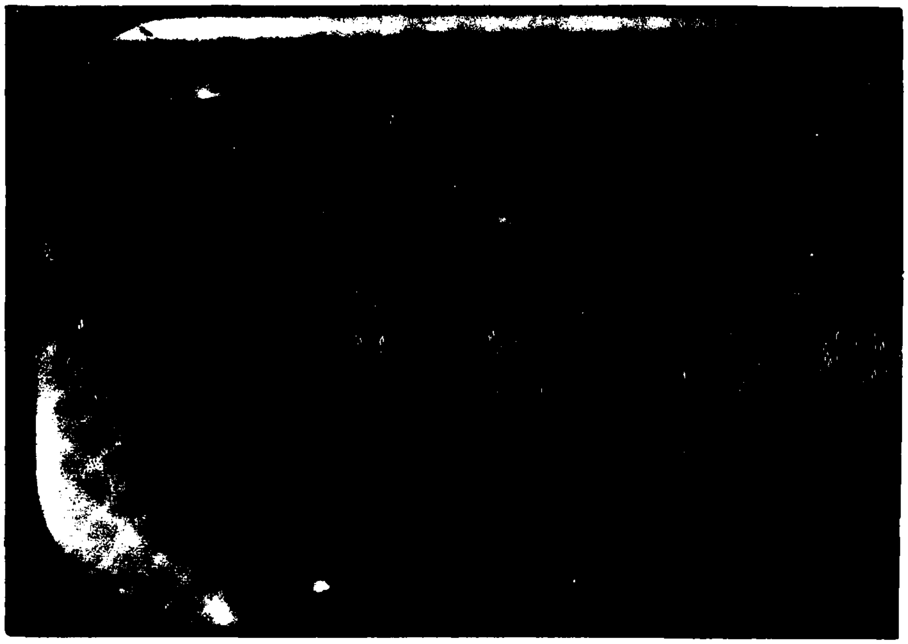


b) Storage mode -- erased to low half-tone.

Figure 3-11 Output from H1349 No. 11.



a) Real-time television mode -- in dark.



b) Storage Mode -- erased to low half-tone.

Figure 3-12 Output from H1349 No. 12.

APPENDIX A

Key Technical Personnel

The following key technical personnel participated in the program:

Personnel	Title	Area of Responsibility
K. R. Hesse	Manager Advanced Display Devices	Program Manager
N. J. Koda	Chief Scientist Image Devices	Consultation
L. S. Yaggy	Senior Scientist	Project Engineer, Tube Design, Fabrication Techniques
D. Mas[illegible]tti	Member Technical Staff	Fabrication Techniques, Diode Array Target
R. S. Morrison	Member Technical Staff	Fabrication Techniques
O. Hoernlein	Member Technical Staff	Fabrication Techniques, Envelope, Electron Gun

APPENDIX B

Publications, Lectures, Reports, and Conferences

There are three items to report belonging to the above categories: two technical conferences and a technical paper. The first technical conference took place on 1 May 1975 at Evans Laboratory, Fort Monmouth, New Jersey. Attendees represented the technical staff of the contracting agency and the technical staff of the contractor. An oral status report of work on the contract was presented by a member of the contractor's staff, and interim use of an available photomask set was discussed. The second technical conference occurred on 12 November 1975 at the same location between representatives of the same organizations. Program status and plans were discussed.

A paper entitled "Storage Camera-Tube with Non-Destructive Readout" was delivered on 6 November 1975 at a meeting of the Society for Information Display in Los Angeles. Subject matter included some of the data obtained on previous contract No. DAAB07-73-C-0330.

APPENDIX C

Computer Study of Reflectivity
of Diode-Array Structure

A computer program entitled TARGET was adapted by Dr. A. I. Braunstein at Hughes Research Laboratories to compute the average transmission at 1.06 μM wavelength of the areas comprising the diode-array. The area consisting of silicon dioxide (SiO_2) and polycrystalline silicon (poly-Si) between the silicon wafer and the vacuum was taken as 52% of the total surface, and the SiO_2-only area as 40%. The remaining 8% representing the center of the diode was treated as a silicon-vacuum interface. Zero absorption in the layers was assumed; therefore, radiation not transmitted was assumed reflected back into the silicon.

Table C-1 is a matrix of computed transmission percentages for combinations of optical thicknesses of the two layers in wavelengths of 1.06 μM. Solutions are seen to occur at 1.30, 1.15 (poly Si, SiO_2 resp.) and at 1.70, 1.35. These solutions repeat at 0.5-wavelength intervals for either layer.

Coincidentally, the solution at 1.70, 1.35 corresponds almost exactly to the normal layer-thicknesses of 1 μM and 0.5 μM, respectively, which had already been adopted. In Ångstrom units, using 3.57 and 1.45 for the respective indices of refraction, the thicknesses are 5050 Å for the poly-Si and 9870 Å for the SiO_2. However, no attempt had been made in the past to control thickness to the extent necessary to avoid significant losses as will occur, for example, at approximately 10% reduction of both thicknesses.

TABLE C-1 AVERAGE TRANSMISSION OF TWO-LAYER STRUCTURE ON DIODE-ARRAY SIDE OF SILICON TARGET

Tabulated values are transmissions in percent. Thicknesses are in wavelengths. The table repeats at half-wave intervals for both layers.

SiO_2 Thickness / Poly Si Thickness	1.0	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40
1.25	68.3	61.0	52.9	50.5	51.0	51.6	51.0	50.5	52.9
1.30	68.3	57.8	51.3	50.0	51.2	52.3	52.4	53.0	57.5
1.35	68.3	57.1	51.9	51.4	53.2	55.0	56.3	59.2	66.8
1.40	68.3	58.7	55.0	55.5	58.3	61.7	65.6	72.3	80.9
1.45	68.3	63.0	62.0	64.8	70.0	76.5	83.4	88.4	86.6
1.50	68.2	70.0	74.6	81.5	88.1	90.9	88.1	84.5	74.6
1.55	68.2	77.5	86.5	88.4	83.3	76.5	70.0	64.7	62.0
1.60	68.2	80.0	80.9	72.2	65.6	61.6	58.3	55.5	55.0
1.65	68.2	74.7	66.8	59.2	56.3	55.0	53.2	51.4	51.9
1.70	68.2	66.9	57.5	53.0	52.4	52.3	51.2	50.0	51.2
1.75	68.2	61.0	52.9	50.4	51.0	51.5	51.0	50.4	52.9

APPENDIX D

Absorption-Coefficient Measurements

The lack of unanimity in published values of the absorption coefficient of silicon at 1.06 μM wavelength made it advisable to attempt a new experimental determination appropriate to this application.

Performance of some tubes at 1.06 μM have appeared to be consistent with coefficients of the order of 25 cm^{-1} or greater. However, it has been impossible to separate the several factors determining the responsitivity with any confidence. Past work was based on the assumption that the absorption-coefficient of the bulk silicon at 1.06 μM, whatever its value, was nearly independent of the doping concentration. This assumption was tested using available material.

Measurements were made which essentially confirmed the low published value of 13 cm^{-1} for very pure silicon (intrinsic, π-type, with approximately 15,000 ohm-centimeter resistivity). A preliminary measurement of the 50 ohm-centimeter n-type material was in the vicinity of 25 cm^{-1}. However, the condition of the samples was such as to recommend postponement of any conclusion.

Samples were prepared from one-ohm-cm material for comparison of results with the 15,000 ohm-cm material, at the other extreme. Measurements of 1.06 μM transmission through these samples gave absorption-coefficients close to 10 cm^{-1}.

Temperature was not tightly controlled during these measurements and may account for some of the differences in data. According to McLean* the effect of temperature is approximately 8% in 10°C near room-temperature.

The method used to check the absorption-coefficient involved two or more slices of a given material having widely differing thicknesses. In every other respect the slices were as nearly identical as possible. In particular, all surfaces had the same polish. Under these conditions a first-order approximation of the abosrption-coefficient, α, can be calculated from the relative magnitudes of the transmitted 1.06 μM radiation:

*in"Progess in Semiconductors",Vol. 5, Wiley & Sons (1960).

$$\alpha \approx \frac{-\ln T_a/T_b}{t_a - t_b}$$

where subscripts "a" and "b" identify the samples of thickness "t" in centimeters, and the T's represent the respective magnitudes of transmitted intensity. This formula takes into account the first reflections from the identical front and back surfaces of the two slices, but ignores the higher-order reflections. This approximation is likely to result in an error of less than 10% with the range of slice-thicknesses used.

Since the materials having resistivities differing by a factor of 15000:1 gave similar results on this check, it seems unlikely that intermediate resistivities have substantially different absorption coefficients.

APPENDIX E

US ARMY ELECTRONICS COMMAND
ELECTRONICS TECHNOLOGY & DEVICES LABORATORY
BEAM, PLASMA & DISPLAY TECHNICAL APFA

TECHNICAL GUIDELINFS BD-24 — 16 May 1974
(supersedes BD-2 dated 25 Sept 72)

STORAGE CAMERA-TUBE WITH NON-DESTRUCTIVE READOUT

1. SCOPE:

These technical guidelines outline a research and development program leading to the design, fabrication, and evaluation of an electron-beam-scanned camera-tube capable of operation either as a real-time camera-tube or as a storage camera-tube with non-destructive readout, the change in function to be accomplished solely as a result of switching from one set of preselected, externally applied voltages operating the imaging section to another corresponding set of voltages for the second function.

2. APPLICABLE DOCUMENTS:

None.

3. REQUIREMENTS:

3.1 General:

The program to be carried out under these technical guidelines shall be directed toward the development of a sealed-off, self-contained, electron-beam-scanned camera-tube with special image-storage features. The camera-tube shall have two individually selectable modes of operation: one, as a normal real-time camera-tube at standard television scanning-rates; and the other, as an image-storage and readout tube, affording continuous readout for an extended period of time of a single "frozen" image. Areas of investigation and performance objectives will include, but will not necessarily be limited to the features outlines in the following paragraphs.

3.2 Detailed Program Objectives:

3.2.1 Physical Size and Weight: The camera-tube is intended for an airborne application. Therefore, the physical size and weight shall be kept to a minimum consistent with the desired operational characteristics. A size comparable with that of an image-return-beam vidicon is suggested.

3.2.2 Spectral Sensitivity Range: The photosensitive surface within the camera-tube must respond both to weak daylight natural illumination from outside scenes and to intentional laser-illumination of specific targets in the near-infrared. Therefore, the spectral sensitivity range shall include with reasonable uniformity the normally-visible wavelength-region from 0.400 through 0.700 micrometer and extend into the near-infrared with comparably useful sensitivity at 1.060 micrometer. Special methods and procedures shall be undertaken as necessary to optimize the sensitivity at 1.060 micrometer.

3.2.3 Operational Modes: The camera-tube shall have two externally selectable operational modes, the details of which will be described in succeeding paragraphs. In the first mode the tuve shall function as a real-time continous-action television camera-tube, while in the second mode the image will be "frozen" into storage at a particular instant of time and will be read out continously without interference from new incoming images.

3.2.4 Operational-Mode Switching: The switching of tube-operation from the real-time television mode to the storage mode and vice-versa shall be accomplished solely by electrical means involving switching the electrode-voltages in the image-section and the storage-target from one set of pre-arranged voltages to a second prearranged set of voltages. No adjustment of these voltages during the sequence of operations shall be required or permitted. The function change from real-time to storage-operation shall be essentially instantaneous, but a short interval of time, on the order of one-ahlf second, may be permitted to erase stored information before resumption of real-time operation.

3.2.5 Preservation of Scan-Geometry: There shall be no perceptible change in the dimensions, nor the linearity, nore the rotational orientation of the scanned-out image occurring as a result of the switching from one mode of operation to the other, except where such change occurs as a result of an intentional change of scale in resumption of the real-time mode after erasure of the stored image.

3.2.6 Preservation of Signal Amplitude: There shall be no more than a 10% change in output signal amplitude, either increasing or decreasing, occurring as a direct result of the switchover from real-time operation of the tubes to storage operation.

3.2.7 Gating of Image: Immediately after an image is frozen into storage upon the storage-target, the imaging section of the tube shall be rendered inoperative by solely electrical means, so that subsequent incoming optical images will not interfere with the stored image during the period of readout of this image. Resumption of real-time operation of the tube will include reactivation of the imaging function.

3.2.8 Readout Storage Duration: Under the operating conditions of the camera-tube appropriate to readout of a stored image, it is desired that the stored image shall be continuously readable without more than 50% degradation of signal modulation amplitude for a duration of at least one minute.

3.2.9 Readout Electron-Beam Deflection: The readout electron beam may be electrostatically or electromagnetically deflected, whichever is more suitable for the contractor's tube design. However, the choice must take into account the objectives of small volume and weight, requirements of high resolution, and compatibility with picture-zoom, as described below.

3.2.10 Picture Zoom: A normal operating procedure with this camera-tube will be to deflect the scan-center of the readout-beam to the location of an object of interest, the designated target, in the wide-angle stored image, so that the image on the readout monitor is centered on this object. Then the scan-amplitudes in the camera-tube will be decreased symmetrically about this center so that the monitor depicts a magnified image of the object in a narrow field-of-view. Such underscanning of the storage-target area shall not be permitted to increase the rate of unintentional fading or decay of the stored image in the area scanned, nor shall a ghost image of the underscanned area be visible in the readouts of the next subsequent full area images, after the normal erasure-sequence. No doctrine of operation is foreseen wherein the scanning of a greater area of a particular stored image would have to be resumed after the scan-amplitude had once been reduced for zoom-operation.

3.2.11 Image-Resolution: Because of the zoom-function expected in the normal operating procedure for this camera-tube, the resolution attributable to the image-section of the camera-tube and the storage-target shall be at least high enough that when the zoom-scan amplitudes are reduced to one-sixth the normal useful amplitudes in both horizontal and vertical directions, the output image-resolution will not be limited by the resolution of the stored image itself.

3.2.12 Output Resolution: With an image of 3 (vertical) by 4 (horizontal) aspect-ratio occupying the maximum useful inscribed area of the storage-target, and with the readout electron-beam adjusted for normal current and best focus at full image-scan, the resolution at the output of the camera-tube shall be at least 1200 television-lines per horizontal scan-line at 5% of maximum contrast-ratio, with a corresponding resolution figure (900 TV-lines) for picture height. The visual input-image shall be a suitable pattern of essentially 100%-contrast black-and-white square-wave bars.

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